

Mixing-Height Time Series from Operational Ceilometer Aerosol-Layer Heights

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Abstract A new method is described to derive mixing-height time series directly from aerosol-layer height data available from a Vaisala CL51 ceilometer. As complete as possible mixing-height time series are calculated by avoiding outliers, filling data gaps by linear interpolation, and smoothing. In addition, large aerosol-layer heights at night that can be interpreted as residual layers are not assigned as mixing heights. The resulting mixing-height time series, converted to an appropriate data format, can be used as input for dispersion calculations. Two case examples demonstrate in detail how the method works. The mixing heights calculated using ceilometer data are compared with values determined from radiosounding data at Vienna by applying the parcel, Heffter, and Richardson methods. The results of the parcel method, obtained from radiosonde profiles at noon, show the best fit to the ceilometer-derived mixing heights. For midnight radiosoundings, larger deviations between mixing heights from the ceilometer and those deduced from the potential temperature profiles of the soundings are found. We use data from two Vaisala CL51 ceilometers, operating in the Vienna area at an urban and rural site, respectively, during an overlapping period of about 1 year. In addition to the case studies, the calculated mixing-height time series are also statistically evaluated and compared, demonstrating that the ceilometer-based mixing height follows an expected daily and seasonal course.

Keywords Aerosol-layer height · Ceilometer · Linear interpolation · Mixing height · Radiosounding

1 Introduction

Within the atmospheric boundary layer (ABL), turbulent properties (diffusivity, mixing, and transport) determine whether pollutants are dispersed and diluted or build up and lead to

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pollution episodes. Thus, the ABL height or mixing height determines the volume available for pollutant dispersion. The mixing height is defined by [Seibert et al. \(2000\)](#) as the height of the layer adjacent to the ground over which pollutants or any constituents emitted within this layer or entrained into it become vertically dispersed by convection or mechanical turbulence within a time scale of about 1 h.

The mixing height at continental mid-latitudes, e.g., in Central Europe, varies markedly with static stability, from a few meters in stable nocturnal conditions to about 2 km in convective conditions during daytime ([Baumann-Stanzer and Groehn 2004](#)). Mixing heights can be calculated from specific parameterizations and preprocessing using either in situ measurements or numerical weather prediction model-derived profiles (for overviews, see [Piringer et al. 2007](#); [Seibert et al. 2000](#)) or diagnosed from observed vertical profiles, classically from radiosondes (e.g., [Piringer et al. 1998](#)) and more recently from sodar, lidar, radar, ceilometer (e.g., [Emeis et al. 2004](#)), and wind profilers ([Bianco et al. 2007](#)). Despite progress in calculating mixing heights from numerical models and estimating mixing heights in particular from ground-based remote sensors, one should be aware that a “mixing-height meter” does not exist ([Seibert et al. 2000](#)), and different definitions, methods, and instruments deliver a range of estimates of mixing height, especially during nighttime and when dilution is dominated by mechanical turbulence.

This paper focuses on derivation of mixing height from ceilometer data. During recent years, this problem has received increasing international attention, e.g., in the framework of EC-COST (European Cooperation in the field of Scientific and Technical Research; [Illingworth et al. 2013](#)). A ceilometer measures the optical backscatter intensity of the air (see Sect. 2), and commercial instruments deliver preprocessed backscatter intensity profiles. The backscatter intensity mainly depends on the particulate concentration in the air. In addition, the reflectivity is also influenced by atmospheric humidity, as the size of many particles varies with their moisture content ([Emeis et al. 2004](#)). Various methods have been proposed to calculate the mixing height from lidar attenuated backscatter profiles ([Münkel 2007](#)), and the proposed methods may be classified into three categories: threshold, variance, and gradient methods ([Illingworth et al. 2013](#)). The threshold method ([Melfi et al. 1985](#)) is based on the assumption that the aerosol load in the free troposphere, above the ABL, is very low. In the ABL, a mixing layer is defined as a zone close to the ground where the backscatter intensity exceeds a fixed threshold. According to [Illingworth et al. \(2013\)](#), this technique requires good signal-to-noise ratio. The variance method employs the temporal variance of the signal to detect the mixing height. A maximum in the aerosol backscatter signal is associated with the entrainment zone, defined as the interface between the mixed layer and the free troposphere. To date, this method has been limited to finding mixing heights in the convective boundary layer ([Illingworth et al. 2013](#)).

The gradient method searches for minima in the gradient of the backscatter intensity. In [Münkel \(2007\)](#), the minimum of the gradient in the range up to 2300 m is given as the top of the mixed layer. Alternative methods take the lowest inflection point in the aerosol backscatter intensity as an indicator of the mixing height ([Illingworth et al. 2013](#)), thus avoiding residual-layer detection at night. In all three categories, aerosol is used as a tracer in the boundary layer, implying that aerosol is emitted at the ground and mixed by turbulence within the boundary layer. In the case of aerosol advection or when aerosol is removed by strong winds, detection of mixing heights from lidar data may be complicated because of the continuity of the aerosol echo between the mixing layer and free troposphere above. As both convection and advection are often commonly present within the ABL, a ceilometer usually detects several minima in the gradient of the backscatter intensity.

Several authors have applied these methods to determine mixing heights from ceilometer data. [De Haij et al. \(2007\)](#) used two algorithms, the first based on analysis of the gradient and the variance, the second using a wavelet transform of the backscatter profile, to deduce mixing heights using a Vaisala-Impulsphysik LD-40 ceilometer. The mixing-height algorithms are not applied in cases with noticeable precipitation. [Eresmaa et al. \(2006\)](#), using a Vaisala CT25K ceilometer, determined the mixing height by fitting an idealized backscatter profile to the observed profile. In the case of a very weak backscatter signal due to very low aerosol concentrations, the mixing height was classified as an outlier and rejected. [Helmis et al. \(2012\)](#) conducted a comparative study of mixing-height estimation based on a Sodar-RASS, an LD-40 ceilometer, and numerical model simulations. For the ceilometer data, the first derivative of the optical attenuated aerosol backscatter intensity was used to determine the mixing height. A noise-dependent gradient threshold was introduced to avoid mixing-height determination due to small fluctuations of the backscatter signal intensity.

Very recently, [Wagner and Schäfer \(2015\)](#) also presented a method to derive mixing heights from data from a Vaisala CL51 ceilometer. The minimum of the vertical gradient in spatially and temporally averaged backscatter profiles was used as an indication of the mixing height, because it is assumed that there is a strong decrease in particle concentration at the top of the mixing layer. The mixing height is considered as invalid when rain or low clouds are present, if strong short-term variations in mixing height occur, or if the minimal vertical gradient (the most negative gradient) of the backscattered signal is not pronounced or is weak. In contrast to all these authors, who determine mixing height by analyzing the backscatter profile, we directly take the lowest aerosol-layer height, a parameter provided by the software of the CL51 instrument, as a basis for mixing-height determination, applying the procedure outlined in Sect. 2.2.

The ceilometers were positioned in the Greater Vienna area, Austria, for about 1 year. Section 2 contains a technical description of the instrument, describes the measurement sites and the area, and explains in detail the method used to derive continuous time series of mixing height from the ceilometers. The results of two case studies demonstrate the quality of the postprocessing tool (Sect. 3.1). A comparison of the ceilometer-derived mixing heights with those deduced from radiosoundings throughout the observation period and a statistical and meteorological analysis of the mixing height from both instruments are presented and discussed in Sects. 3.2 and 4, while Sect. 5 contains a summary.

2 Materials and Methods

2.1 Instruments and Measuring Sites

Zentralanstalt für Meteorologie und Geodynamik (ZAMG), the governmental weather service in Austria, operates two Vaisala CL51 ceilometers. The first is located in Vienna at the Central Institute for Meteorology and Geodynamics (16.3564°E, 48.2483°N, 198 m a.s.l.) and operated continuously since 3 July 2012. The second was situated in Obersiebenbrunn (16.700°E, 48.267°N, 150 m a.s.l.), a village approximately 26 km east of Vienna, with data available between 18 July 2013 and 13 June 2014. The sites are shown in Fig. 1. Vienna, the capital of Austria, has 1.8 million inhabitants and is situated at the eastern rim of the Alps.

The CL51 ceilometer employs diode-laser lidar technology, with which short, powerful laser (light amplification by stimulated emission of radiation) pulses with wavelength of

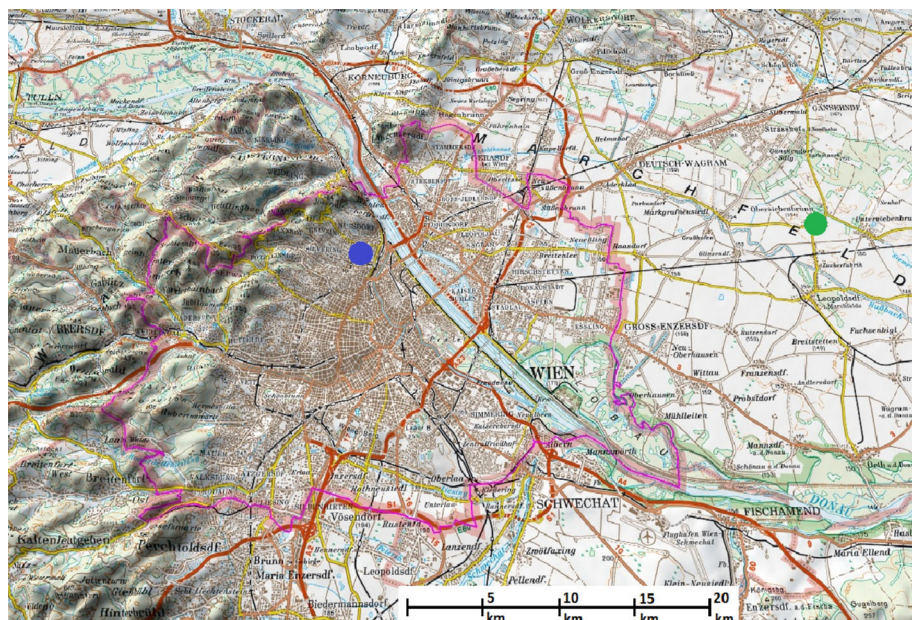


Fig. 1 Measuring sites of the two Vaisala CL51 ceilometers. *Blue dot* Wien Hohe Warte site. *Green dot* Obersiebenbrunn site. The map is taken from “Austrian Map Fly 5.0” from the Federal Office for Calibration and Measurement in Austria (Bundesamt für Eich- und Vermessungswesen)

910 ± 10 nm (infrared light) are sent out in a vertical or near-vertical direction. The laser source of the CL51 ceilometer is an eye-safe indium gallium arsenide diode. The single-lens optics of the ceilometer enables detection in a measurement range above approximately 50 m above ground level, where sufficient overlap of emitted and backscattered laser signals is achieved (Wagner and Schäfer 2015), up to 15 km. A sketch of the optical configuration can be found in Emeis et al. (2008) or Münkel and Roininen (2010).

Reflection of light, backscatter caused by clouds, precipitation, haze, fog, mist, and virga, is measured as the laser pulses traverse the sky. The time delay between the launch of a laser pulse and the detection of a backscatter signal indicates the cloud-base height. The CL51 ceilometer can detect three cloud layers simultaneously. The backscatter profile is further used to detect up to three aerosol-layer heights (also referred to by Vaisala as “boundary-layer heights”) by applying the so-called gradient method mentioned above with postprocessing software (BL-VIEW), which includes an automated mixing-height detection (aerosol-layer height detection) algorithm as described in Emeis et al. (2007). The BL-VIEW software from Vaisala, which is used to analyze data from both CL31 and CL51 ceilometers, includes a “cloud and precipitation filter,” termed the “enhanced gradient method” by Vaisala and described in Münkel and Roininen (2010). This method identifies the high backscatter signal from clouds and precipitation and excludes it from the averaging process before applying the gradient method.

For this study, data from both ceilometers for the time period from 18 July 2013 to 13 June 2014 were used. In this time period, backscatter plots, up to three cloud heights, and up to three aerosol-layer heights are available. The height resolution is 10 m, and the maximum vertical range is 13 km.

2.2 Method to Derive Mixing-Height Time Series from Aerosol-Layer Height Data

The mixing-height time series were derived based on the following basic assumptions:

- Aerosols and polluted air emitted near the ground disperse vertically primarily up to the lowest aerosol-layer height.
- The vertical aerosol distribution adapts rapidly (within 1 h) to the changing thermal structure of the ABL.

The output of the BL-VIEW ceilometer software consists of a text file for each day. Every file includes up to three cloud-base heights and up to three aerosol-layer heights with temporal resolution of 16 s. This time interval is a result of the limit on data transfer from the ceilometer to the personal computer where the data are processed. For determination of mixing height, only the lowest aerosol-layer height data were used. Since the mixing height is the result of either convective or mechanical turbulence, additional wind data from a surface synoptic observation (SYNOP) station near the ceilometer are important and were also used to determine the mixing height within the postprocessing program described herein. In the following description of the postprocessing tool, the lowest aerosol-layer height is referred to as the aerosol-layer height.

Herein, mixing height is meant in the sense defined by [Seibert et al. \(2000\)](#) given earlier. The mixing height is thus the upper lid to which pollutants, emitted near ground level, are dispersed. Following this definition, the three basic principles to determine mixing height from aerosol-layer height are: the lowest aerosol-layer height is taken as the mixing height; large heights at night interpreted as residual layers are excluded by considering the near-ground wind speed (careful data analysis revealed that low near-ground wind speeds do not occur with high aerosol-layer height values); and the mixing height is not determined when extended gaps in aerosol-layer height occur, mostly due to clouds or rain. All aerosol-layer height data are, as a first step, converted to a time interval of 5 min. The provisional result is a time series of aerosol-layer height data with time resolution of 5 min for the whole time period.

Day–night separation of aerosol-layer height is obtained by determining, for each time step, the sun’s elevation angle to the “real” horizon as a function of the geographical coordinates of the ceilometer and the day of the year. This separation is important to discriminate nocturnal aerosol-layer height values representing an elevated residual layer from those associated with a near-surface stable or inversion layer. Only the latter is seen as relevant for nighttime mixing-height determination. Therefore, all nocturnal aerosol-layer height values over 500 m are excluded from mixing-height determination. For wind speeds $< 3 \text{ m s}^{-1}$, all nocturnal aerosol-layer height values above 250 m are additionally excluded, resulting in considerably lower average mixing heights than without this procedure. Neither the height nor the wind speed threshold is fixed, but each depends on local conditions and has to be determined for each new site.

At this stage, the aerosol-layer height time series might still show considerable short-term variations. In the next calculation step, outliers of aerosol-layer height within the whole time period are removed. Therefore, a moving average of aerosol-layer height is calculated for each (5 min) timestep by considering time-neighbouring values. The number of aerosol-layer height values to be averaged can be selected by the user. If the difference between the moving average of the aerosol-layer height and the current value of the aerosol-layer height exceeds a certain threshold (e.g., 150 m, selectable), the current value of aerosol-layer height is treated as an outlier and is replaced by the moving average value at this point of time. If all outliers

for the entire time period are replaced by the current moving-average value, the corrected time series of aerosol-layer height can be regarded as a provisional result.

There are situations that cause a gap in the time series of aerosol-layer height data, such as heavy rain, poor signal-to-noise ratio, and power failure. Also, the removal of nocturnal aerosol-layer height values detected within residual layers or advected aerosol layers (see above) produces data gaps. These data gaps are filled by linear interpolation between the last usable aerosol-layer height value before the data gap and the next usable aerosol-layer height value after the data gap, if the gap is not too long. The maximal gap length to be filled is selectable and in this investigation was limited to 6 h. To avoid unrealistic jumps still present in the time series, the entire time series is smoothed by a moving average, in which the number of averaged values is selectable. The result is a mixing-height time series with 5-min resolution. Finally, averaging the 5-min mixing-height values over, e.g., half an hour, the resulting mixing-height time series can be used as an input for a dispersion model.

This method has the following advantages:

- Unrealistic high nocturnal aerosol-layer height values detected from residual layers or advected layers are eliminated.
- Outliers are removed.
- Aerosol-layer height data gaps with length up to 6 h are filled by linear interpolation. If there are no aerosol-layer height data gaps exceeding 6 h, the availability of the resulting mixing-height time series can achieve 100 %.
- Unrealistic jumps within the resulting mixing-height time series are avoided by smoothing.
- The resulting mixing-height time series is converted to a data format appropriate for further use in a dispersion model.

2.3 Methods for Mixing-Height Comparison

In Sect. 3, the mixing heights derived from ceilometer data by the procedure described in Sect. 2.2 are compared with those derived from routine radiosoundings. There are two radiosoundings per day at Vienna, at 0000 UTC and 1200 UTC, measuring vertical profiles of temperature, dew point, wind direction, and wind speed. These are used for comparison. Three methods are applied to derive the mixing height from vertical potential temperature profiles: the Heffter, parcel, and Richardson methods (Piringer and Lotteraner 2010). A criterion used to analyze potential temperature profiles for so-called critical inversion heights was originally formulated by Heffter (1980) and later explained and used by Marsik et al. (1995), whereby the mixing height is the level within the lowest layer with potential temperature lapse rate equal to or larger than 5 K km^{-1} , where the temperature is 2 K higher than at the base of the stable layer. The parcel method (Holzworth 1967) is based on following the dry adiabat from the measured surface temperature to its intersection with the temperature profile of the associated radiosounding. Thus, the mixing height is taken as the equilibrium level of an air parcel with this temperature, but depends on a superadiabatic lapse rate at the ground and the existence of a pronounced inversion at the top of the convective boundary layer (CBL). The third method is based on the bulk Richardson number approach (e.g., Vogelesang and Holtslag 1996), which can be used in all atmospheric stability conditions. Mixing heights are determined as the height at which the Richardson number exceeds a critical value, usually taken as 0.25, although a wide range of values between 0.2 and 3 have been used (Piringer et al. 2007).

3 Results

This section is intended to demonstrate if and how, with a commercial ceilometer such as the Vaisala CL51, as continuous as possible mixing-height information can be obtained for use in dispersion models. This is first shown for two case studies, highlighting the approach used to derive a continuous time series of mixing height from aerosol-layer height data, followed by a statistical analysis of the whole time period of almost 1 year, for which data from two CL51 ceilometers in the Vienna area are available. The analysis was carried out to investigate whether CL51 ceilometers can successfully reproduce the general mixing-height pattern expected for Central Europe as well as local differences between sites. The quality of mixing-height determination from the ceilometers is checked by comparison with mixing-height estimates from radiosoundings throughout the data period.

3.1 Case Examples for Mixing-Height Time Series

Figure 2a shows a CL51 backscatter intensity plot recorded at Wien Hohe Warte on 3 October 2013 and the corresponding radiosoundings (Fig. 2b–d) recorded at 0000 UTC and 1200 UTC. This was an anticyclonic day without clouds, an ideal situation to demonstrate the procedure to determine the mixing height. The colours in the intensity legend indicate the intensity of the backscatter signal in units of $10^{-9} \text{ m}^{-1} \text{ sr}^{-1}$: light-blue to yellow colour in the plot indicates the intensity of the aerosol backscatter signal; black dots or lines indicate aerosol-layer heights determined by the BL-VIEW software from Vaisala. The bold yellow line indicates the mixing-height time series for this day calculated by the method explained in Sect. 2.2, and the red marks within the backscatter intensity plot at 0000 UTC and 1200 UTC indicate the mixing-height values calculated by the Heffter (He), parcel (Pa), and Richardson (Ri) methods from the radiosonde potential temperature profile (Fig. 2b–d). On this day, the wind speed did not exceed 3 m s^{-1} until sunrise (at approximately 0600 UTC), so only aerosol-layer height values with a maximum of 250 m were used for the mixing-height calculation during this period. After sunset (at around 1730 UTC), the wind speed continuously exceeded 3 m s^{-1} , therefore only aerosol-layer height values with a maximum of 500 m were used. Because of this limitation of the vertical range of nocturnal aerosol-layer height values, erroneous determination of the residual layer (above 1000 m) as the mixing height was avoided. There were enough low-level aerosol-layer height data points that the gap-filling mechanism described in Sect. 2.2 was successful. During the whole day, only the lowest aerosol-layer height values were used for calculation of mixing height (Sect. 2.2); the smoothing described in Sect. 2.2 avoids unrealistic jumps and causes the curved trend of the mixing height (Fig. 2a).

From the vertical profiles of potential temperature in Fig. 2, the mixing height was calculated by the methods outlined in Sect. 2.3 and compared with the ceilometer estimates (Table 1). These mixing-height values from the radiosoundings at 0000 UTC and 1200 UTC are marked as short red lines in the backscatter intensity plot in Fig. 2a. At 0000 UTC, the parcel method could not be applied because of the missing superadiabatic layer near the ground (Seibert et al. 2000). However, all the mixing-height values that could be calculated from radiosonde data fit well with the mixing-height values calculated from the aerosol-layer height data on this “ideal,” fair-weather day.

The next case example (Fig. 3) demonstrates how the method to determine mixing height performs on a day with a complex structure of aerosol-layer heights and with precipitation. Figure 3a shows the backscatter intensity plot recorded at Obersiebenbrunn on 10 September 2013 and the corresponding radiosoundings (b–d) recorded at 0000 UTC and 1200 UTC.

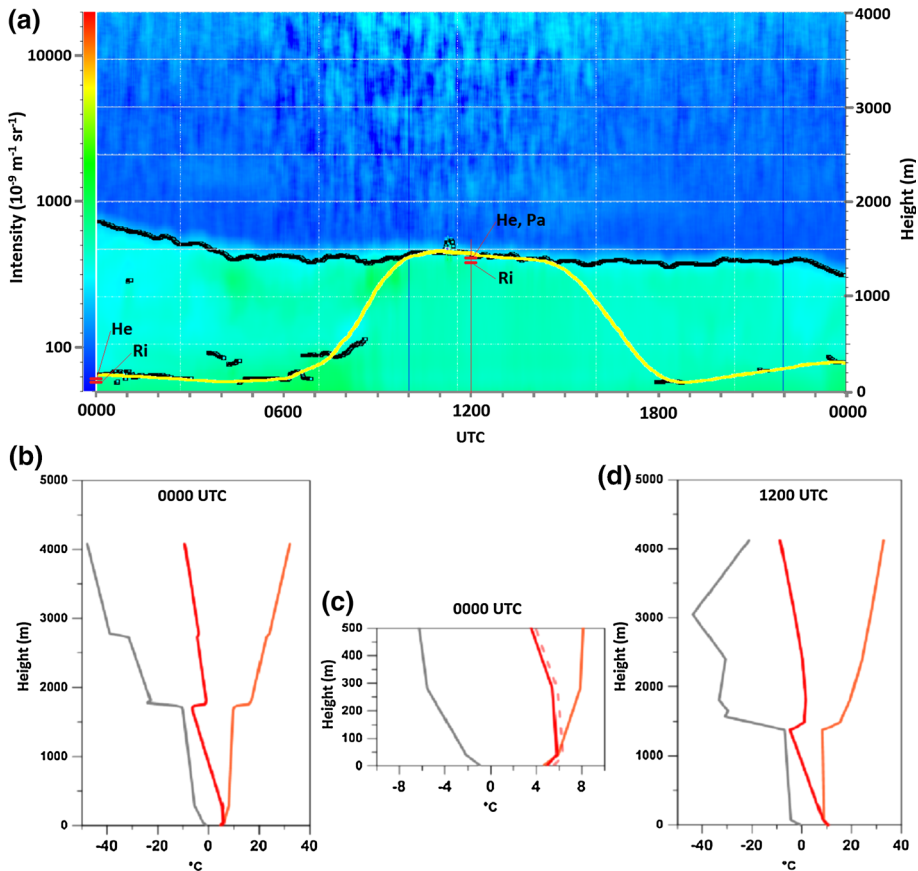


Fig. 2 a CL51 backscatter intensity plot with calculated mixing-height time series (yellow line) recorded at Wien Hohe Warte on 3 October 2013. The red marks in the backscatter intensity plot indicate the mixing-height values calculated by the Heffter (He), parcel (Pa), and Richardson (Ri) methods. **b–d** Corresponding radiosoundings recorded at 0000 UTC (**b, c**) and 1200 UTC (**d**) with vertical profiles of temperature (red), virtual temperature (dashed red line), dew point (grey), and potential temperature (orange)

Table 1 Values of mixing height (m) determined by the ceilometer at Wien-Hohe Warte and radiosounding data from Vienna on 3 October 2013

	Mixing height (Ceilometer)	Mixing height (Heffter method)	Mixing height (Parcel method)	Mixing height (Richardson method)
0000 UTC	186	139		94
1200 UTC	1462	1403	1401	1355

This day was characterized by an overcast sky up to 0300 UTC in the morning, broken clouds during daytime, and intermittent rain starting at approximately 1900 UTC. The colours in the intensity legend indicate the intensity of the backscatter signals in units of $10^{-9} \text{ m}^{-1} \text{ sr}^{-1}$. Red colour in the plot denotes precipitation and clouds; light-blue to yellow colour in the plot indicates the intensity of the aerosol backscatter signal. Black dots or lines indicate

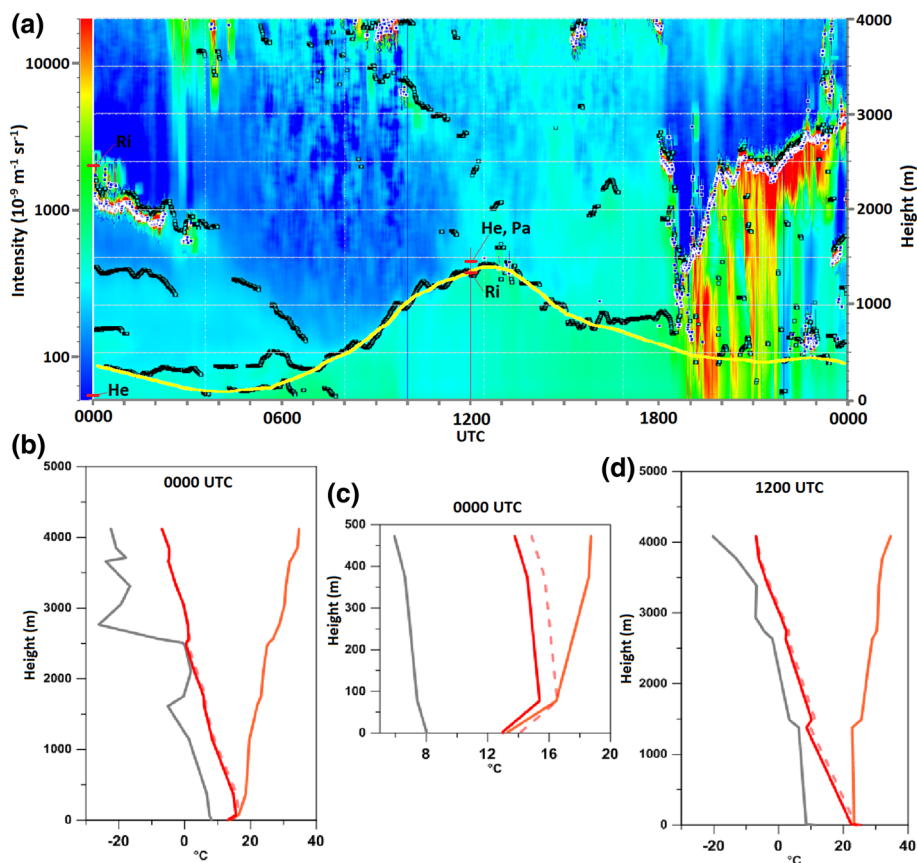


Fig. 3 a CL51 backscatter intensity plot with calculated mixing-height time series (yellow line) recorded at Obersiebenbrunn on 10 September 2013. The red marks in the backscatter intensity plot indicate the mixing-height values calculated by the Heffter (He), parcel (Pa), and Richardson (Ri) methods. **b–d** Corresponding radiosoundings from Wien Hohe Warte recorded at 0000 UTC (**b**, **c**) and 1200 UTC (**d**) with vertical profiles of temperature (red), virtual temperature (dashed red line), dew point (grey), and potential temperature (orange)

aerosol-layer heights, and white-rimmed dots or lines indicate cloud heights as determined by the BL-VIEW software from Vaisala. The bold yellow line indicates the mixing-height time series for this day calculated by the method mentioned in Sect. 2.2. The red marks within the backscatter intensity plot at 0000 UTC and 1200 UTC indicate the mixing-height values calculated by the Heffter (He), parcel (Pa), and Richardson (Ri) methods. Until sunrise at around 0530 UTC, the wind speed did not exceed 3 m s^{-1} , therefore only aerosol-layer height values up to 250 m were used to determine the mixing height. Until 0330 UTC, the aerosol-layer height values exceed 250 m and could therefore not be used. Thus, linear interpolation was carried out beginning from the last usable aerosol-layer height value (on the day before) to the first aerosol-layer height value at the permitted maximum of 250 m at around 0330 UTC on this day. Between sunrise and sunset, the mixing-height course follows more or less the aerosol-layer height course, but in a smoothed form. Only between 1630 and 1800 UTC does the resulting mixing-height course have an almost linear shape, which is caused on the one hand by very strong smoothing and on the other hand by linear interpolation. It turned out that

Table 2 Values of mixing height (m) determined by the ceilometer at Obersiebenbrunn and radiosounding data from Vienna on 10 September 2013

	Mixing height (Ceilometer)	Mixing height (Heffter method)	Mixing height (Parcel method)	Mixing height (Richardson method)
0000 UTC	360	49		2467
1200 UTC	1350	1460	1459	1345

Table 3 Availability (%) of aerosol-layer height data in comparison with availability (%) of mixing height data

Measurement site	Aerosol-layer height	Aerosol-layer height (after removal of unrealistic nocturnal values)	Mixing height
Wien Hohe Warte	77	58	81
Obersiebenbrunn	61	53	73

the smoothing effect (by the moving average) should be reduced in future analyses. Yellow and red colours in the backscatter intensity plot (between 1900 and 2400 UTC) indicate rain. During this nighttime period, aerosol-layer height values up to 500 m were used to calculate the mixing-height course, as ground-level wind speeds exceeded 3 m s^{-1} . In spite of several gaps in aerosol-layer height data and rain for several hours in the evening, a continuous mixing-height time series with 100 % availability of mixing-height data could be calculated by applying the method described in Sect. 2.2.

The analysis of the vertical radiosonde profiles of potential temperature at 0000 UTC and 1200 UTC on this day yields the results stated in Table 2 and marked in Fig. 3. The mixing-height value at 0000 UTC determined by the Richardson method coincides with the cloud layer. Because of the distinct ground inversion at 0000 UTC (Fig. 3c) the mixing-height value according to the Heffter method is only 49 m. This low-level inversion is not detected by the ceilometer. At 1200 UTC, the ceilometer mixing-height values and the mixing-height values according to the Heffter, parcel, and Richardson methods are similar because of a clear capping inversion.

3.2 Long-Term Comparison of the Mixing Height from the Ceilometers

Depending on the (selectable) maximum duration of data gaps to be filled by linear interpolation and also on the time period, the availability of mixing-height data in the resulting time series can ideally reach up to 100 %. For this study, a maximum duration of data gaps of 6 h was selected. As the case studies in Sect. 3.1 show, this helps to determine the mixing height especially at night when the aerosol-layer height time series is frequently interrupted. On the other hand, this time period is not so long as to cause large errors in mixing-height determination, e.g., across sunrise or sunset. If the duration of a data gap exceeds 6 h, no linear interpolation is carried out, and the gap is not filled. Table 3 presents the availability of the calculated mixing-height data in comparison with the availability of the original aerosol-layer height data as well as the availability of aerosol-layer height data after removal of high

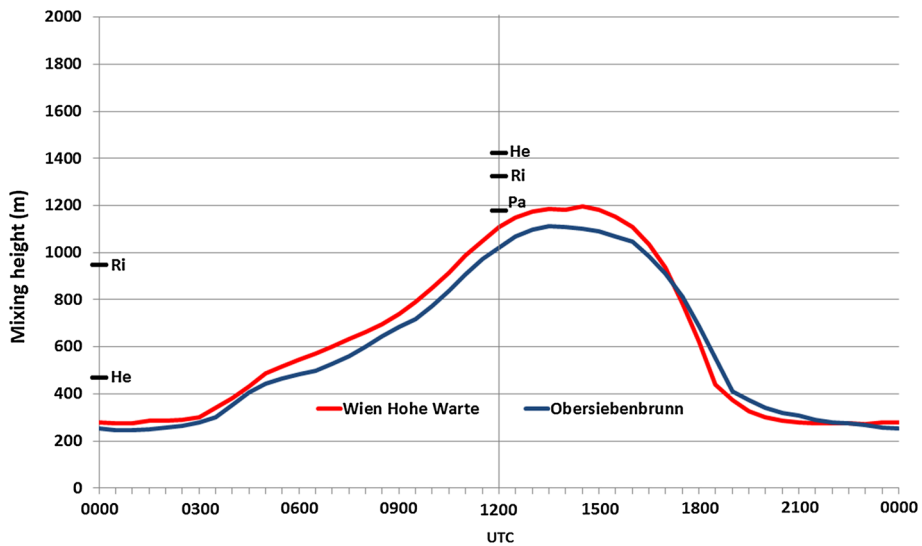


Fig. 4 Mean diurnal variation of mixing height calculated from ceilometer data in Vienna (Wien Hohe Warte) and Obersiebenbrunn near Vienna in the time period from 18 July 2013 to 13 June 2014. The black marks indicate the means of the mixing-height values calculated by the Heffter (He), parcel (Pa), and Richardson (Ri) methods

nocturnal values attributed as marking the residual layer in the time period from 18 July 2013 to 13 June 2014. Apparently, data gaps exceeding the selected 6-h limit are quite frequent, both at Wien Hohe Warte and at Obersiebenbrunn. The gap-filling procedure described in Sect. 2.2 increases the percentage of mixing-height values over that of the original aerosol-layer height data. The intention of this procedure is to increase the number of mixing-height values available for dispersion calculations as far as possible by simultaneously minimizing the number of unrealistic mixing-height estimates.

Based on a statistical comparison of the mixing height from the two ceilometers, we now investigate whether or not the data are meteorologically plausible. An appropriate means to check this involves the mean diurnal variation of the mixing height, which, in continental Europe, should be significant, as are seasonal differences. These expectations are generally confirmed in Fig. 4, where the maximum daytime mixing height is about 1100 m at Obersiebenbrunn and about 1200 m at Wien Hohe Warte, and the minimum nighttime mixing height is below 300 m. As expected, the mean diurnal variation of mixing height is more pronounced during the summer months (April–September) than during the winter months (October–March, Fig. 5). In summer, the average maximum daytime mixing height reaches 1600 m, and in winter around 800 m. In summer, the morning increase in mixing height occurs earlier, and the afternoon decrease later, compared with winter. The black and grey marks in Figs. 4 and 5 indicate the mean values of the mixing height at 0000 UTC and 1200 UTC calculated from radiosonde data from Vienna after applying the Heffter, parcel, and Richardson methods. A comparison of the means of the mixing-height values calculated from ceilometer data and from radiosonde profiles from Vienna at 0000 UTC and 1200 UTC is also presented in Table 4. It turns out that the means of the mixing-height values calculated by the Heffter and Richardson methods are higher than the means of the mixing-height values derived from ceilometer data. The noon estimates from the parcel method fit quite

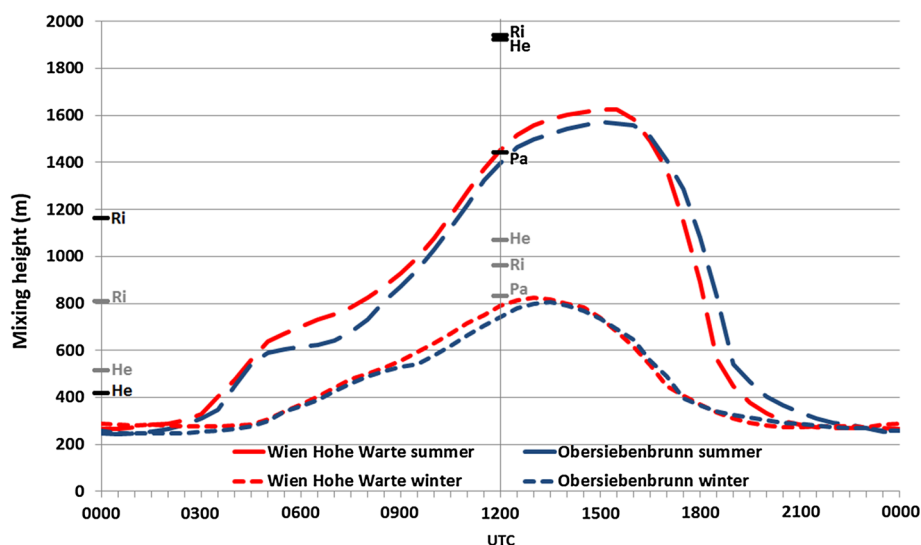


Fig. 5 Mean diurnal variation of mixing height calculated from ceilometer data in Vienna (Wien Hohe Warte) and Obersiebenbrunn near Vienna for summer and winter in the time period from 18 July 2013 to 13 June 2014. The black (summer) and grey (winter) marks indicate the means of the mixing-height values calculated by the Heffter (He), parcel (Pa), and Richardson (Ri) methods

Table 4 Long-term comparison of mean mixing-height values (m) calculated from ceilometer data and from radiosonde profiles from Vienna at 0000 UTC and 1200 UTC applying the Heffter, parcel, and Richardson methods in the time period from 18 July 2013 to 13 June 2014

	Total		Winter		Summer	
	0000 UTC	1200 UTC	0000 UTC	1200 UTC	0000 UTC	1200 UTC
Wien Hohe Warte ceilometer	278 (212)	1109 (302)	287 (114)	791 (157)	267 (98)	1454 (145)
Obersiebenbrunn ceilometer	252 (199)	1022 (255)	257 (117)	741 (146)	246 (82)	1399 (109)
Heffter	473 (327)	1426 (297)	518 (180)	1076 (175)	419 (147)	1928 (122)
Parcel		1184 (229)		833 (97)		1442 (132)
Richardson	953 (282)	1332 (263)	808 (169)	965 (164)	1169 (113)	1940 (99)

Numbers in parenthesis are the numbers of (half hourly) mixing-height values

well with the mixing-height estimates from the ceilometer, especially at Wien Hohe Warte, where the radiosonde is launched. This result is encouraging, as the parcel method is the most physically sound method to derive mixing heights from potential temperature profiles. Nighttime mixing-height estimation remains a challenge. Apparently, the settings in the post-processing tool to determine mixing heights from ceilometer aerosol-layer height data lead to very similar estimates of mixing height at Wien Hohe Warte and Obersiebenbrunn, thus masking possible urban (heat island) effects expected to increase the nighttime urban mixing height. However, it is also shown in Figs. 4 and 5 that the means of the mixing height from radiosonde data differ distinctively between the Heffter and Richardson number methods during nighttime.

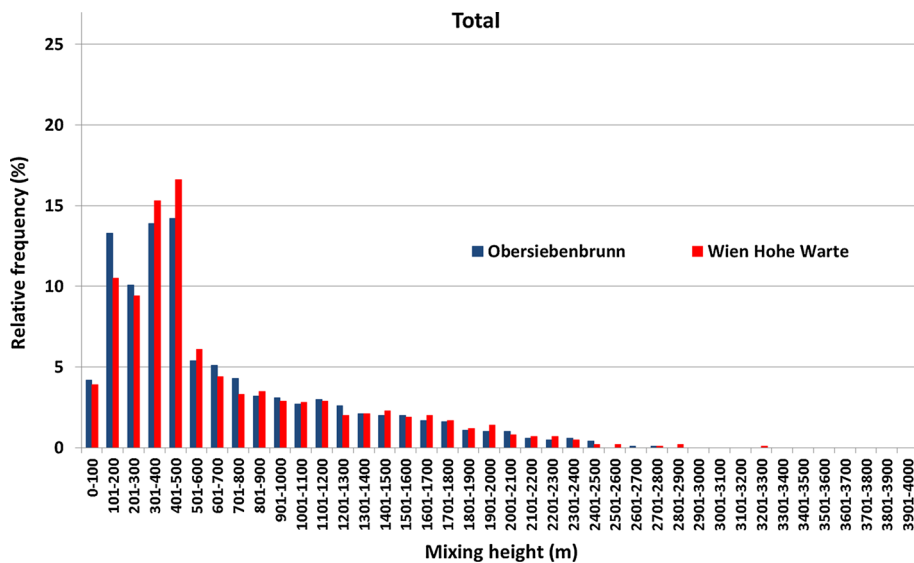


Fig. 6 Distribution of relative frequency of mixing height calculated from ceilometers in Vienna (Wien Hohe Warte) and Obersiebenbrunn near Vienna for the time period from 18 July 2013 to 13 June 2014. The mixing height values are separated into classes of 100 m

A further indication of expected urban–rural differences in mixing height is obtained from the distributions of the relative frequency of mixing-height values as displayed in Fig. 6 for the whole dataset and in Fig. 7 for selected time periods. At both sites, mixing heights between 100 and 500 m are most frequent, with about 10 to 16 % in each 100-m class (Fig. 6). Mixing height values up to 100 m have a frequency of about 4 %. This demonstrates once more the ability to detect also stable surface layers using the CL51 ceilometer. Mixing-height values up to 300 m are more frequent at Obersiebenbrunn, but mixing-height values from 301 to 600 m are more frequent at Vienna. This is consistent with the expectation that very shallow mixing heights occur more frequently over rural than urban terrain. Over an urban area, shallow mixing heights might be elevated compared with rural surroundings due to the urban-heat-island effect. On average, these differences are not very pronounced (see Figs. 4 and 5).

Detailed investigation of seasons and daytime versus nighttime shows large differences between summer and winter as well as day and night (Fig. 7). The highest mixing-height values can be found, as expected, during the summer months in the daytime (Fig. 7a). In a broad range between 200 and 1800 m, each mixing-height class occurs with frequency of approximately 5 %. A distinct maximum of the relative frequency of mixing-height values during daytime with values over 10 % can be found in winter months between 300 and 600 m (Fig. 7b). During nighttime in both summer (c) and winter (d), most of the mixing-height values do not exceed 500 m because of the elimination of aerosol-layer height values over 500 m by the method described in Sect. 2.2 to avoid detection of the residual layer as the mixing height. Especially in winter, only a few cases with mixing height above 500 m remain. In spite of this limitation on the aerosol-layer height values during nighttime, there are some mixing height values exceeding 500 m because of the linear interpolation; For example, in case of high aerosol-layer height values (e.g., 2000 m) before sunset and a following large aerosol-layer height data gap, linear interpolation until the next nocturnal aerosol-layer height

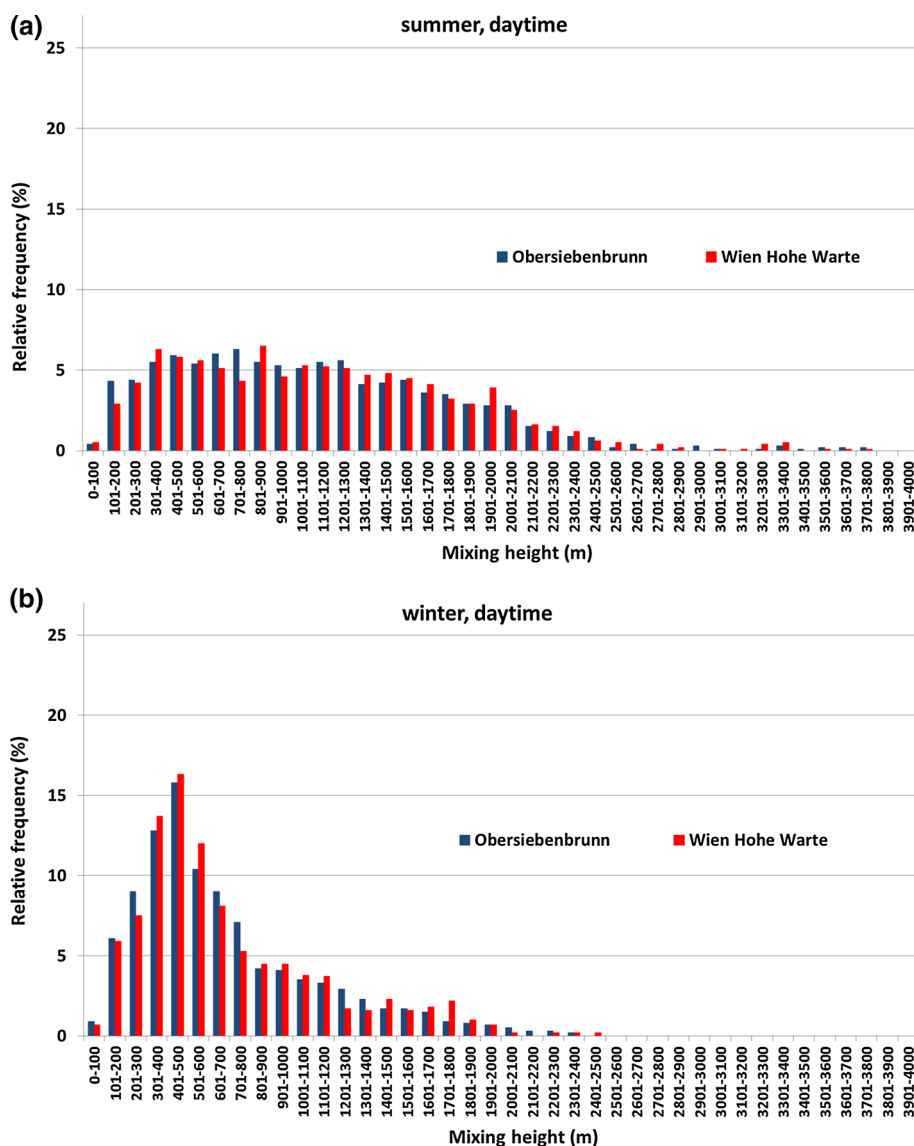


Fig. 7 Distributions of relative frequency of mixing-height values calculated from ceilometer data in Vienna (Wien Hohe Warte) and Obersiebenbrunn near Vienna in the time period from 18 July 2013 to 13 June 2014, separated into summer (April–September) and winter months (October–March), as well as daytime and nighttime. The mixing-height values are separated into classes of 100 m

value (which is limited to 500 m) may result in some mixing-height values exceeding 500 m. The same occurs if there is a large data gap during nighttime followed by high aerosol-layer height values immediately after sunrise.

The scatterplot in Fig. 8 displays the correlation between the mixing-height values of both ceilometers for the time period from 18 July 2013 to 13 June 2014. The bold black line indicates the linear regression line. As can be seen from Fig. 8, the mixing-height values

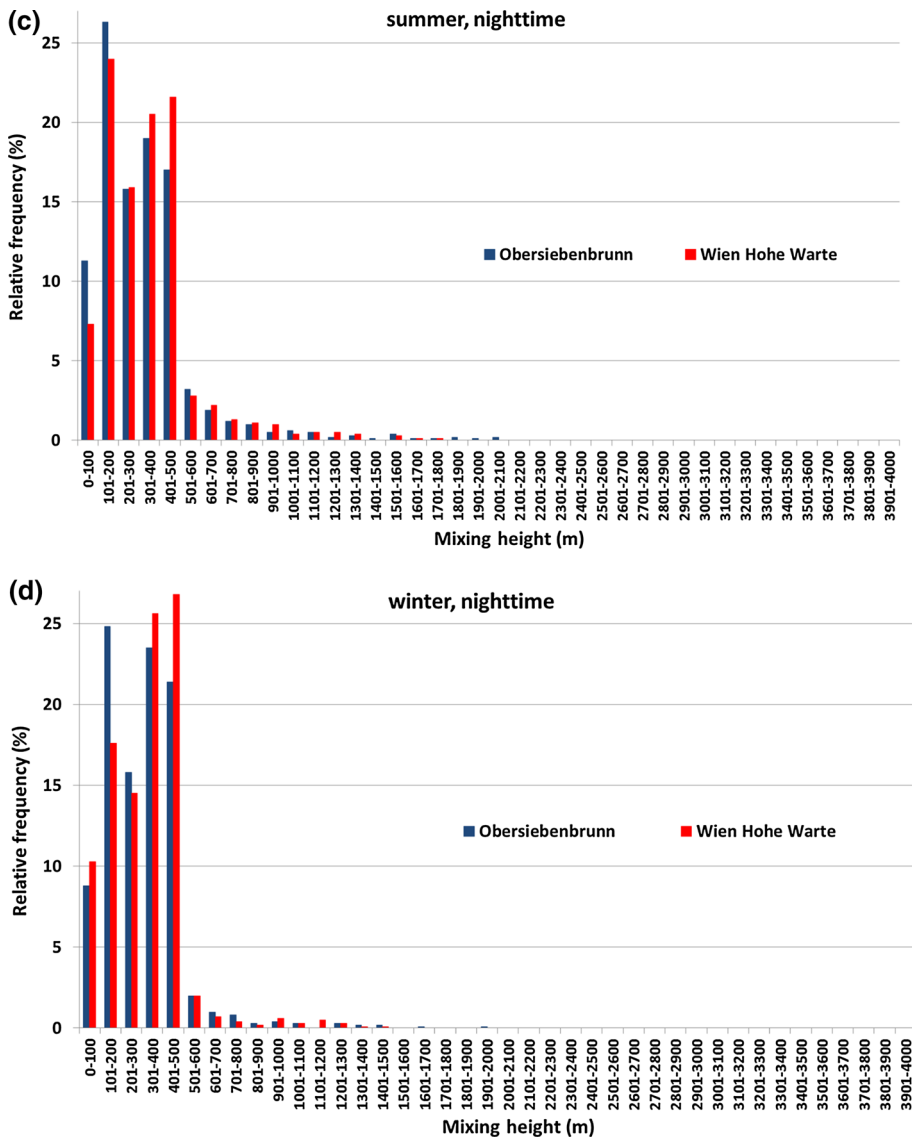


Fig. 7 continued

tend to cluster along the 1:1 line (thin line in Fig. 8), but in some cases the mixing-height values from the two ceilometers are also very different. From visual inspection of Fig. 8, no systematic bias can be seen. There is a slight tendency for higher mixing heights at Vienna compared with Obersiebenbrunn, as also seen in Figs. 4, 5, 6, and 7. One reason for this scatter is of course the spatial distance of approximately 26 km between these two ceilometers. More important is the different characteristics of the Earth's surface between Vienna (urban influence) and Obersiebenbrunn (rural influence) and the resulting differences in mixing height. Data pairs with large differences between the sites (in the upper left and

Fig. 8 Scatterplot of mixing height from the ceilometers at Vienna (Wien Hohe Warte) and Obersiebenbrunn during the time period from 18 July 2013 to 13 June 2014; *bold line* shows the linear regression line

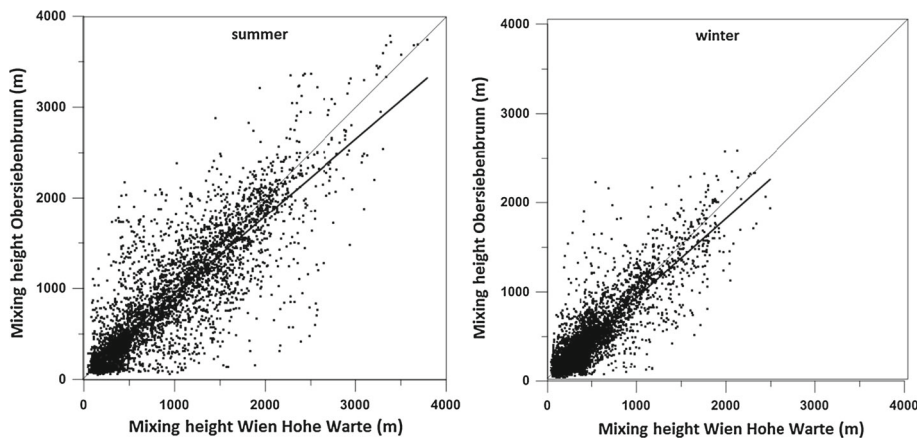
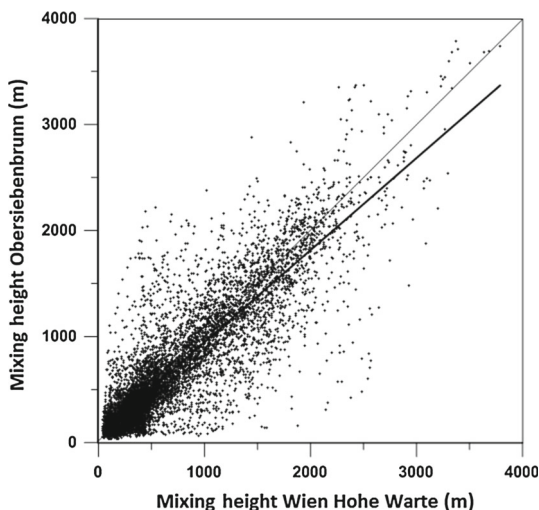


Fig. 9 Scatterplot of mixing height from ceilometers at Vienna (Wien Hohe Warte) and Obersiebenbrunn during summer (*left*) and winter (*right*) within the time period from 18 July 2013 to 13 June 2014; *bold lines* show linear regression lines

lower right of Figs. 8 and 9) probably indicate that the ceilometers used different aerosol-layer heights to determine the mixing height.

Seasonal differences are displayed in Fig. 9. The two plots clearly indicate the systematically larger mixing heights in summer compared with winter. During winter, most of the mixing-height values are clustered up to approximately 700 m (right plot in Fig. 9). The course of the regression lines, as in Fig. 8, indicates the already discussed tendency towards slightly larger mixing heights at the predominantly urban site at Wien Hohe Warte compared with the strongly rural-classified Obersiebenbrunn.

The correlation coefficient, coefficient of determination, and root-mean-square error (*RMSE*) for the mixing-height time series of the two ceilometers in the time period from 18 July 2013 to 13 June 2014 are specified in Table 5. Due to the relatively short distance between the ceilometers, the correlation is quite high, indicating that local effects do not

Table 5 Correlation coefficient, coefficient of determination, and root-mean-square error (*RMSE*) for the time period from 18 July 2013 to 13 June 2014

	Total	Summer	Winter
Correlation coefficient	0.87	0.85	0.86
Coefficient of determination	0.76	0.73	0.73
<i>RMSE</i>	288.4	362.2	204.0

Table 6 Maximum, minimum, mean, standard deviation, and number of (half-hourly) mixing-height values (m) calculated from data from the ceilometers at Vienna (Wien Hohe Warte) and Obersiebenbrunn near Vienna in the time period from 18 July 2013 to 13 June 2014

	Mixing height at Wien Hohe Warte	Mixing height at Obersiebenbrunn
Maximum	3790	3913
Minimum	40	40
Mean	679	630
Standard deviation	583	553
Number of (half-hourly) values	12,301	10,453

often determine the mixing height at both sites. The scatter in the data is smaller in winter compared with summer. The maximum values of mixing height (Table 6) are unexpectedly high; however, such mixing-height values are very rare (Fig. 7). The minimum values of mixing height (Table 6) demonstrate that the CL51 ceilometer can detect the surface layer.

4 Discussion

Over the last few decades, the abundance and accuracy of mixing-height information have increased considerably. Earlier, radiosonde potential temperature profiles were mainly used (e.g., [Holzworth 1967](#)), with the disadvantage of providing, as a rule, only two profiles per day for analysis. In Europe, fortunately, radiosonde ascents are conducted near midday and midnight, so near-maximum and near-minimum mixing heights can be obtained (e.g., [Piringer et al. 1998](#)). A long tradition exists in estimating continuous mixing-height information from sodar backscatter profiles ([Weill and Lehmann 1990](#); [Beyrich 1997](#); [Piringer et al. 2004](#)), but only with the addition of radio acoustic sounding system antennae that measure virtual temperature profiles could the uncertainty be reduced considerably ([Emeis et al. 2004](#); [Hennemuth and Kirtzel 2008](#)). However, the problem of the low vertical range of a few hundred meters above ground remains, preventing determination of the full diurnal cycle of mixing height from such measurements, especially under convective conditions in summer. This disadvantage is overcome by wind profilers, which have delivered, for more than two decades, estimates of the depth of the convective boundary layer predominantly in clear-sky conditions (e.g., [Bianco et al. 2007](#); [Angevine et al. 1994](#)). Operational wind profilers can be used to detect the annual variability of the daytime mixing height, as demonstrated by [Bianco et al. \(2011\)](#) for California's Central Valley. Another promising instrument for mixing-height detection is the microwave radiometer, which measures vertical profiles of temperature and humidity, but there are no mature solutions to date ([Illingworth et al. 2013](#)).

With the arrival of advanced software for ceilometers, which were originally and have for several decades been used for detecting cloud-base heights primarily at airports, their backscatter profiles can be analyzed more profoundly, also enabling detection of mixing heights (Sect. 2.2). Due to the vertical range of ceilometers of at least a few kilometers, the full diurnal cycle of mixing height can in principle be obtained. Ceilometers, in contrast to the instruments mentioned above, have the advantage of being relatively cheap and easy to maintain. Restrictions arise from limitations inherent to the ceilometer, such as heavy rain, dense fog, and poor signal-to-noise ratio; also, power failures can interrupt measurements. When used as input for dispersion models, as continuous as possible mixing-height time series are needed, e.g., to calculate yearly averages or percentiles of concentrations. That is why the postprocessing tool described in Sect. 2.2 was developed to derive as continuous as possible time series of mixing height from the aerosol-layer heights provided by the CL51 ceilometer.

In this study, data from two ceilometers, one in the grounds of the Central Institute for Meteorology and Geodynamics in Vienna (Wien Hohe Warte; urban) and the other in the village of Obersiebenbrunn 26 km east of Vienna (rural), were evaluated for the period from 18 July 2013 to 13 June 2014. The quality of the postprocessing tool described in Sect. 2.2 is first demonstrated in two case studies (Sect. 3.1), one for a clear day and one for a partly cloudy and rainy day. Based on these case studies, the details of the procedure to determine the mixing height from the lowest aerosol-layer height of a ceilometer are outlined. The three basic principles to determine the mixing height from the aerosol-layer height are as follows: The lowest aerosol-layer height is taken as the mixing height; large heights at night (interpreted as residual layers) are excluded by considering the near-ground wind speed; and the mixing height is not determined when extended gaps in the aerosol-layer height occur. On the fair-weather day (Fig. 2), the mixing height calculated from the ceilometer data corresponds well to the mixing height determined from the midnight and noon radiosonde profiles using different methods, because the potential temperature profiles show distinct inversions. In addition, the procedure to fill gaps in the aerosol-layer height data, especially during nighttime, can be demonstrated to be successful. On the cloudy and partly rainy day (Fig. 3), the procedure to avoid erroneous detection of the residual layer as the mixing height is clearly demonstrated. Due to a sufficient amount of aerosol-layer height data points, it was even possible to obtain a mixing-height time series during the intermittent rain event in the evening of that day. The comparison between the mixing height obtained from the ceilometer and that derived from radiosonde measurements was good for noon but not for midnight, where the estimates from the radiosounding differed by more than 1000 m, as the mixing height determined by the Richardson number method was near the elevated cloud layer, whereas the Heffter method found a shallow mixing height because of strong ground-based inversion.

This investigation also tried to demonstrate the ability of commercial Vaisala CL51 ceilometers to deliver plausible time series for mixing height over a longer period. The investigation revealed that the two ceilometers delivered average daily courses and frequency distributions of mixing height as expected for continental Central Europe (Figs. 4, 5, 6, and 7). This finding is not obvious. Past comparisons revealed considerable shortcomings of measurement devices for determination of mixing height, especially for sodars (Seibert et al. 2000; Piringer et al. 2004).

The comparison between the mixing heights derived from the ceilometers and those diagnosed from radiosonde profiles was best during daytime, when pronounced capping inversion was found in the potential temperature profile (Fig. 2). In conditions when the capping inversion was only weak or almost nonexistent, as with overcast skies, strong winds or rain,

i.e., when mechanical turbulence dominates over thermal turbulence, deviations have to be expected also during daytime. The only method which takes into account mechanical turbulence is the Richardson method. The parcel and Heffter methods rely on vertical temperature profiles only. In Central Europe, fair-weather conditions during noon radiosoundings account for approximately one-third of all cases, so that also on average significant deviations in mixing height between the methods occur (Figs. 4, 5). Overall, the mixing-height estimates by the parcel method fit best with the mixing height determined from the aerosol-layer heights from the ceilometer, a result which strengthens confidence in the daytime ceilometer estimates, as the parcel method has a sound physical basis.

There remains considerable uncertainty concerning reliable determination of mixing height at night. Seibert et al. (1998) state that, especially under stable conditions, when the intensity of turbulence is relatively weak, it might be very difficult to find a clear upper boundary of the mixing layer. Complete agreement between mixing heights estimated by different methods can therefore not be expected. Figure 3 shows a striking example of this uncertainty. Also, COST-Action 715 (Piringer et al. 2007) arrived at the conclusion that the mechanisms involved in the formation of the daytime mixing height, especially under convective conditions, are better understood than the corresponding nocturnal ones. In the current investigation, mixing-height estimates from the ceilometer were forced, by analyzing the near-ground wind speed, to be as low as possible to avoid detection of residual layers, which usually show a much stronger echo in the backscatter profile than near-ground stable layers. This forcing might add to the deviations of mixing-height estimates for the Richardson and Heffter methods. However, these two methods themselves deliver mixing heights which differ significantly on average during nighttime (Figs. 4, 5). The results of the Richardson method depend on the accuracy of the radiosonde wind profile and whether wind data are well resolved near the ground; in addition, the choice of the critical Richardson number will have an influence on the results. The results of the Heffter method depend on the choice of the limit value for the temperature lapse rate per km and the value for the strength of the inversion. The deviations between all the methods applied in this study are best seen in Table 4.

Baumann-Stanzer and Groehn (2004) used a dense network of radiosoundings established in the Austrian–Swiss Rhine Valley during the Mesoscale Alpine Programme (MAP) field phase and also found differences in mixing height when applying the methods presented in Table 4. The Richardson number method sometimes detected the height of the residual layer at night. Results for Munich (Piringer et al. 2007) on the basis of the CALRAS (Comprehensive Alpine Radiosonde; Häberli 2001) dataset for the period 1991–1999 with high vertical resolution, are analogous to those in Table 4, showing a similar increase of mixing height from the parcel to the Heffter and Richardson methods during daytime. They found strong differences in nighttime mixing height between urban- and rural-influenced radiosoundings (depending on whether the air mass crossed the city of Munich or not), where the Heffter method gave on average larger estimates of mixing height than the Richardson method.

De Haij et al. (2007) conducted a comparison of mixing-height estimates from a LD-40 ceilometer with those from radiosondes at De Bilt, determined with the Richardson and parcel methods. For all data, they found only weak agreement and a tendency to overestimate the mixing height by the radiosondes. The agreement improved considerably when only ceilometer mixing heights of high quality determined with the wavelet method were used. Eresmaa et al. (2006) found a correlation coefficient of 0.80 and a mean difference of 73 m between their ceilometer mixing-height estimates and those determined from radiosoundings at Helsinki in stable conditions using the Richardson number method. Wagner and Schäfer (2015) attribute the on-average slightly higher mixing-height values from the CL51 ceilome-

ter compared with those derived from radiosoundings with the Richardson method in their study to the fact that the ceilometer was operated in the city centre of Essen whereas the radiosondes were launched in a suburban area.

Direct comparison of the mixing height between Wien Hohe Warte and Obersiebenbrunn (Fig. 8) reveals agreement, but also some scatter, despite the short distance of 26 km between the two sites. Most probably, local conditions can influence the mixing height at both sites, giving rise to occasional large differences in mixing height. The two sites are distinct in their local surroundings: Wien Hohe Warte is suburban, on a south-east-oriented slope with small inclination, and the area is covered by scattered buildings, mostly surrounded by gardens with some trees. The built-up area of Vienna lies east to south of the site and affects it with easterly winds. To the north and west, the suburban area continues and finally turns into forested hills, the so-called Wienerwald. The site is thus subject to a slope wind system, with rapid warming in the morning and also rapid cooling in the evening, on anticyclonic days. The summertime daily course of mixing height at Wien Hohe Warte (Fig. 5) can be explained by these local features: the morning increase and afternoon decrease in mixing height are more rapid at Wien Hohe Warte compared with Obersiebenbrunn. The ceilometer at Obersiebenbrunn was situated in a garden, surrounded by village houses; the wider area there is flat and used agriculturally. The classification “rural” is therefore not very strict, as even small villages can exert some anthropogenic influences, e.g., on the sensible heat flux, especially during wintertime due to domestic heating.

The sometimes large differences in mixing height between the two sites, notable from Figs. 8 and 9, can be attributed to the fact that, at the same time, different aerosol-layer heights are considered for mixing-height determination, at least during daytime. In the majority of cases, however, the mixing heights cluster along the 1:1 line, with a tendency towards higher mixing heights at Wien Hohe Warte. The increased mixing height over urban areas compared with their rural surroundings is attributed to enhanced mixing, resulting from large surface roughness and increased surface heating (Piringer et al. 2007). The evaluation of ceilometer-derived mixing height reveals only very slight nighttime differences between higher urban and lower rural mixing heights, on average (Fig. 5). This might be a result of having chosen neither an ideal urban nor an ideal rural site, thus minimizing differences, but might also be an outcome of the algorithm described in Sect. 2.2 to suppress the detection of the residual layer as the mixing height.

5 Conclusions

A new method, directly taking available aerosol-layer height data from a Vaisala CL51 ceilometer, is applied to calculate mixing-height time series by removing unrealistic nocturnal aerosol-layer height values, avoiding outliers, filling data gaps by linear interpolation, and smoothing. The method is outlined in Sect. 2.2. The resulting mixing-height time series, converted to an appropriate data format, is as complete as possible and can thus be used as input for dispersion calculations.

For this study, data from two Vaisala CL51 ceilometers, which were operated together between 18 July 2013 and 13 June 2014, were used; one ceilometer was situated at Wien Hohe Warte, and the other at Obersiebenbrunn at a distance of approximately 26 km (Sect. 2.1). This setup allowed analysis of possible site-specific influences on mixing height. Moreover, the ceilometer-based mixing heights are compared with values derived from radiosoundings using the parcel, Heffter, and Richardson methods (Sect. 2.3) throughout the operation period.

For two selected days, a case study was carried out to explain in detail how the mixing height is derived from the lowest aerosol-layer height from a CL51 ceilometer (Sect. 3.1). On the fair-weather day (Fig. 2), erroneous determination of the nighttime residual layer (above 1000 m) as the mixing height was avoided, and also the gap-filling mechanism was successful. On the partly cloudy and rainy day (Fig. 3), a continuous mixing-height time series could be calculated during the rain event in the evening as enough aerosol-layer height data points were available.

The statistical evaluation (Sect. 3.2) revealed that the ceilometers can detect the daily and seasonal course of mixing height expected for Central Europe (Figs. 4, 5). As expected, low mixing-height values are more frequent in winter than summer months and are more frequent during nighttime than daytime (Figs. 6, 7). The on-average larger mixing height at the urban site during daytime in summer (Fig. 5) can be explained by local features: the site is on a south-east-facing slope and thus subject to a slope wind system, with rapid warming in the morning and also rapid cooling in the evening, on anticyclonic days. Therefore, the morning increase as well as afternoon decrease in mixing height are more rapid at Wien Hohe Warte compared with Obersiebenbrunn. The ceilometer mixing heights were compared with those diagnosed from radiosoundings at 0000 and 1200 UTC with the parcel, Heffter, and Richardson methods (Sect. 2.3). The best agreement was found for the parcel method at noon (Figs. 4, 5). This result strengthens confidence in the daytime ceilometer estimates, as the parcel method has a sound physical basis. The Heffter and Richardson methods tend to overestimate the mixing height in comparison with the ceilometers. During nighttime, this might also be caused by the algorithm used to avoid detection of the residual layer as the ceilometer mixing height (Sect. 2.2). Scatterplots (Figs. 8, 9) showing the differences in mixing height between Wien Hohe Warte and Obersiebenbrunn reveal clustering of data pairs along the 1:1 line and many data pairs with small mixing-height differences, but also some scatter. The correlation is quite high, indicating that local effects do not often determine the mixing heights at both sites (Table 5). Data pairs with large differences can probably be explained by the fact that the ceilometers used different aerosol-layer heights for mixing-height determination, especially during daytime. A tendency for slightly higher mixing-height values at Wien Hohe Warte compared with Obersiebenbrunn can also be seen from these plots; this is attributed to enhanced vertical mixing over the urban area. The minimum value of the calculated mixing-height time series using aerosol-layer height data from the considered time period is 40 m (Table 6), which demonstrates that the CL51 ceilometer can detect the surface layer.

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